NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS
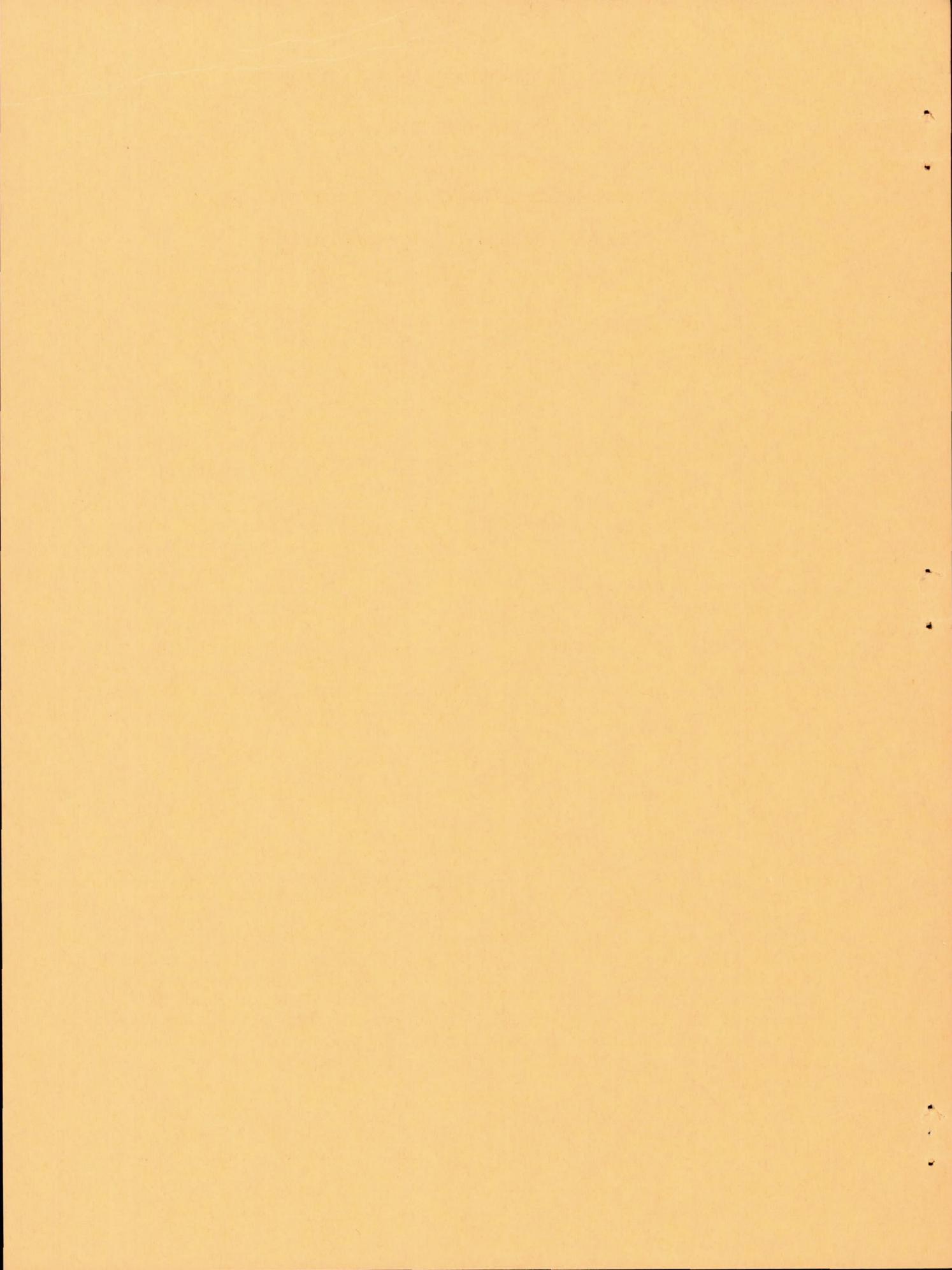
TECHNICAL NOTE 4410

FLIGHT MEASUREMENTS OF THE VIBRATORY STRESSES ON A

PROPELLER DESIGNED FOR AN ADVANCE RATIO

OF 4.0 AND A MACH NUMBER OF 0.82

By Thomas C. O'Bryan

Langley Aeronautical Laboratory
Langley Field, Va.

NACA

Washington
September 1958

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 4410

FLIGHT MEASUREMENTS OF THE VIBRATORY STRESSES ON A

PROPELLER DESIGNED FOR AN ADVANCE RATIO

OF 4.0 AND A MACH NUMBER OF 0.82

By Thomas C. O'Bryan

SUMMARY

Results are presented of vibratory-stress measurements obtained in flight on a propeller designed for an advance ratio of 4.0 and a forward Mach number of 0.82.

The vibratory bending stress was low throughout the flight range. The maximum stress was only ±3,700 pounds per square inch at a forward Mach number of 0.66. Bending stress was primarily once-per-revolution (1-P) for Mach numbers up to 0.84. For higher Mach numbers the stress assumes a more complicated wave shape as it approaches a minimum.

The maximum torsion stress occurred during a ground run in which the blade was stalled. The blade was fluttering but it was sufficiently stiff to keep the stress below ±5,000 pounds per square inch. The maximum torsional stress measured in flight did not exceed ±1,000 pounds per square inch.

INTRODUCTION

Airplane propellers designed to operate efficiently at high subsonic Mach numbers are characterized by thin blade sections operating at near-optimum advance angle. A propeller embodying both of these characteristics is reported on in references 1 and 2. Some relaxation of the requirement of optimum advance angle has been shown in reference 3 to have little effect on the efficiency. Although the optimum propeller of reference 1 is efficient, it is quite noisy. The propeller of reference 3, operating at higher than optimum advance angle, is much quieter because of its lower tip speed. In an effort to reduce the noise further and at the same time to find an end point in the relaxation of the requirement of optimum advance angle, the present propeller was investigated.

The vibratory stresses of major importance are the 1-P and stall flutter stresses. The 1-P stress is the stress that occurs once per revolution, caused by the oscillating aerodynamic load imposed on the propeller as a result of inclination of the thrust axis (refs. 4 and 5). The use of thin blade sections results in a more flexible blade, which in turn lowers the natural bending frequency to a value closer to the operating rotational speed with attendant magnification of the 1-P stress. Use of thin blades results in low values of torsional frequency and thus makes the blade more susceptible to stall flutter (ref. 5).

The propeller of this investigation was designed for an advance ratio of 4.0, compared with 2.2 and 3.2 for the propellers of references 1 and 3. A similar thickness distribution was used (2 percent at 0.75 radius) and in addition the blades were cambered, whereas the blades of references 1 and 2 were symmetrical. Because of the limited rotational speeds available the propeller diameter had to be reduced, so that only 25 percent of available power could be absorbed efficiently under take-off conditions.

This report presents flight measurements of the vibratory bending and torsion stresses, which are indicative of the 1-P and flutter stresses, for a propeller with an advance ratio of 4.0. Results are presented for level-flight conditions at approximately 30,000 feet and forward Mach numbers up to 0.96.

SYMBOLS

A local angle of inclination of thrust axis with free stream
           at propeller plane, deg

b blade chord, ft

C_L design lift coefficient of propeller

D propeller diameter, ft

h blade thickness, ft

M free-stream Mach number

q dynamic pressure, lb/sq ft

r radius of an element on blade from center line of rotation, ft

$x = 2r/D$

β blade angle, deg

EQUIPMENT

The propeller is a three-blade configuration of 6.85-foot diameter, designed for a forward Mach number of 0.82 and an advance ratio of 4.0. The blades are of solid steel machined from SAE 4340 steel forgings and have a rectangular plan form with NACA 16-series airfoil sections. The design lift coefficient is 0.50 outboard of the 35-percent radius station. The thickness varies from 0.077 chord at the 35-percent radius station to 0.02 chord at the 80-percent radius station, and then has a constant value of 0.02 chord to the tip. The blade-form curves are shown in figure 1.

The propeller has an experimentally determined first natural (non-rotating) bending frequency of 28.3 cps and a first torsion frequency of 115 cps.

The propeller was tested in conjunction with an elliptical spinner that was 55 inches long and 30.2 inches in diameter at the propeller plane. A photograph of the spinner and propeller is presented in figure 2. The blade seals shown in the photograph are alined with the spinner surface at the design advance ratio to provide an aerodynamically smooth surface.

The test vehicle was the XF-88B propeller-research airplane. General specifications of the airplane can be found in reference 1. A turboprop engine drives the propeller at 1,710 rpm. An overall view of the airplane is presented in the photograph of figure 3.

INSTRUMENTATION

One of the propeller blades was instrumented with four strain-gage bridges for measuring vibratory bending strain and one bridge for measuring vibratory torsional strain. The bridges were located on the blade center line, with the bending gages at the 35.0-, 37.5-, 38.7-, and 41.1-percent radius station and the torsion gage at the 72.5-percent radius station. The gages were located so as to bracket the positions of maximum vibratory stress that were calculated by the method of reference 6.

A four-component strain-gage bridge was located at each strain-measuring station. The four gages were used to acquire the desired output sensitivity and to cancel gage outputs due to centrifugal forces and minimize the effect of temperature changes. The output of the strain-gage bridges was recorded on an oscillograph. The galvanometers used to

record bending strain had a response curve that was flat to 100 cps; the galvanometer that recorded torsion strain was flat to 190 cps.

The Aq factor, or the product of the local angle of inclination of thrust axis with free stream and the dynamic pressure, was determined during flight tests without a propeller installed under the flight conditions for which stress was measured. Angle determination is considered accurate to $\pm 0.2°$.

The source of static and total pressure for the calibrated airspeed system was a Kollsman type 651 pitot-static head, mounted 1 tip-chord length ahead of the wing tip of the airplane. The impact pressure and static pressure were recorded with a standard NACA airspeed recorder. The Mach number was determined from a radar calibration to be accurate within ± 0.005 for Mach numbers reported on herein. Measurements of airplane normal acceleration, propeller root blade angle, and propeller rotational speed were made with standard NACA instrumentation.

TESTS AND PROCEDURE

Strain-gage records were obtained during essentially level flight at approximately 30,000 feet while the airplane was being accelerated to maximum Mach number by increasing the main-jet power and then entering a shallow dive. The power coefficient of the propeller during the tests varied from 1.59 to 2.36, the thrust coefficient varied from 0.43 to 0.46, and the advance ratio ranged up to 4.9.

The stress values were determined from visual inspection of the strain-gage records, simply by reading amplitudes throughout the record length whenever there were significant variations in strain.

RESULTS AND DISCUSSION

Vibratory Bending Stress

Wave-shape analysis.- Bending data were obtained at the 35.0-, 37.5-, 38.7-, and 41.1-percent radius stations. Two typical examples of the recorded wave shape of the vibratory bending stress are presented in figure 4. The example in figure 4(a) is representative of the wave shape existing for Mach numbers up to 0.84. In this case the shape indicates that the vibration is that occurring at a frequency of once per revolution (1-P). The example of wave shape above $M = 0.84$ (fig. 4(b)) changes from mostly 1-P to a more complicated form as the stress approaches a minimum and the inclination of the thrust axis

approaches zero. The variation of the envelope amplitude from maximum to minimum stress correlates with the short-period oscillation of the airplane as determined from the normal-accelerometer record. The airplane, and thus the thrust axis, is oscillating through zero angle to a small positive and negative angle at twice the frequency of the airplane short-period oscillation of approximately 2.5 seconds.

Stress measurements.- The variations of the vibratory bending stress and the excitation factor Aq are presented in figure 5 as functions of Mach number. The vibratory bending stress measured at the four stations decreases with increasing Mach number in the same manner that Aq decreases. The location of maximum measured stress at the 35-percent radius station agrees well with the calculated value at the 37.5-percent radius station. The maximum vibratory bending stress was ±3,700 pounds per square inch at $M = 0.66$. The similar variation of the stress with Aq is a further indication of the 1-P stress previously noted by observation of the wave shape of the vibration.

The ratio of stress to Aq as a function of Mach number is presented in figure 6 for the maximum stress location (35-percent radius station). For the design conditions of $M = 0.82$, the maximum experimentally determined ratio of stress to Aq is 4.3 at the 35-percent radius station, which is in fair agreement with the theoretical value of 3.0 at the 37.5-percent radius station calculated by the method of reference 6. The ratio decreases smoothly from a value of 5.3 at $M = 0.68$ to about 4.0 at $M = 0.84$. This decrease in the ratio of stress to Aq as the Mach number increases is thought to be a result of loss of lift in the outboard sections as the resultant tip Mach number exceeds 0.90. Above $M = 0.84$ the variation is no longer smooth, the data scattering with no pattern between ratios of 3 and 30. This scatter results from the fact that the percentage error in Aq is high when the value of A is small. In addition, the stress is low and the variation is therefore of little interest.

The vibratory bending stresses that the propeller might be subjected to through the normal flight-test range of the XF-88B airplane can be estimated from reference 2. This reference presents the variation of Aq with Mach number for the range of altitude and maneuver load factors through which the airplane is normally operated. The maximum experimental ratio of 1-P stress to Aq of 5.3 used in conjunction with the Aq of reference 2 determines the stress. The maximum excitation factor that could be expected with the XF-88B airplane in the range of Mach numbers of this investigation would be 1,330 pound-degrees per square foot for a maneuver load factor of 2.0g at 30,000 feet and a Mach number of 0.75. The resulting 1-P stress would be 7,060 pounds per square inch. This is a low value of stress for a steel propeller and is not representative of a full-scale model. The power absorption

is low; under static conditions the propeller absorbs a maximum of
1,100 horsepower. To absorb the maximum power available from the
T-38 engine installed in the XF-88B (2,500 horsepower) would require a
diameter of 20 feet in a three-blade configuration or 15 feet in a four-
blade configuration. An exact geometric scaling of the blade to absorb
more power would result in a reduction in the 1-P bending stress and con-
sequently in ratio of stress to Aq. The stress is reduced because the
section modulus increases more rapidly than does the bending moment due
to increased aerodynamic loading. It might be desirable from an instal-
lation standpoint to scale the blade for increased power absorption to
fit the hub used in this investigation. This hub is capable of handling
much larger blades than the ones tested. Scaling the blade to absorb
much more than double power would increase the 1-P stress, as the bending
moment would begin to increase more rapidly than the section modulus.
This is due to the increase in moment arm resulting from the use of a
fixed-diameter hub at the same time the blade diameter is increased.

Vibratory Torsion Stress

In whirl tests of a four-blade configuration, the blades were stalled
during the test with no evidence of flutter. The torsion-stress data
were obtained from strain measurements at the 72.5-percent radius station
with the three-blade configuration installed on the XF-88B airplane.

The maximum vibratory torsion stress measured in flight is presented
as a function of Mach number in figure 7. The stress did not exceed
±1,000 pounds per square inch. The variation with Mach number follows
the 1-P stress variation (fig. 5) very closely; the wave shape is 1-P
with a very small amplitude at the natural torsion frequency imposed on
it.

The maximum torsion stress occurred during a ground run in which
the blade was stalled. The blade was fluttering but it was sufficiently
stiff to keep the stress below ±5,000 pounds per square inch.

SUMMARY OF RESULTS

Results are presented of vibratory-stress measurements obtained in
flight on a propeller designed for an advance ratio of 4.0 and a forward
Mach number of 0.82.

The vibratory bending stress was low throughout the flight range.
The maximum stress was only ±3,700 pounds per square inch at a forward
Mach number of 0.66. Bending stress was primarily once-per-revolution
(1-P) for Mach numbers up to 0.84. For higher Mach numbers the stress
assumes a more complicated wave shape as it approaches a minimum.

The maximum torsional stress occurred during a ground run in which the blade was stalled. The blade was fluttering but it was sufficiently stiff to keep the stress below ±5,000 pounds per square inch. The maximum torsional stress measured in flight did not exceed ±1,000 pounds per square inch.

Langley Aeronautical Laboratory,
    National Advisory Committee for Aeronautics,
        Langley Field, Va., September 10, 1958.

REFERENCES

1. Hammack, Jerome B., Kurbjun, Max C., and O'Bryan, Thomas C.: Flight Investigation of a Supersonic Propeller on a Propeller Research Vehicle at Mach Numbers to 1.01. NACA RM L57E20, 1957.

2. O'Bryan, Thomas C.: Flight Measurements of the Vibratory Bending and Torsion Stress on a Supersonic-Type Propeller for Flight Mach Numbers up to 0.95. NACA RM L56D20a, 1956.

3. O'Bryan, Thomas C.: Flight Measurements of the Vibratory Bending and Torsional Stresses on a Modified Supersonic Propeller for Forward Mach Numbers up to 0.95. NACA TN 4342, 1958.

4. Gray, W. H., Hallissy, J. M., Jr., and Heath, A. R., Jr.: A Wind-Tunnel Investigation of the Effects of Thrust-Axis Inclination on Propeller First-Order Vibration. NACA Rep. 1205, 1954. (Supersedes NACA RM L50D13.)

5. Baker, John E.: The Effects of Various Parameters, Including Mach Number, on Propeller-Blade Flutter With Emphasis on Stall Flutter. NACA TN 3357, 1955. (Supersedes NACA RM L50L12b.)

6. Arnoldi, Walter E.: Response of a Rotating Propeller to Aerodynamic Excitation. NACA RM 8I07, 1949.
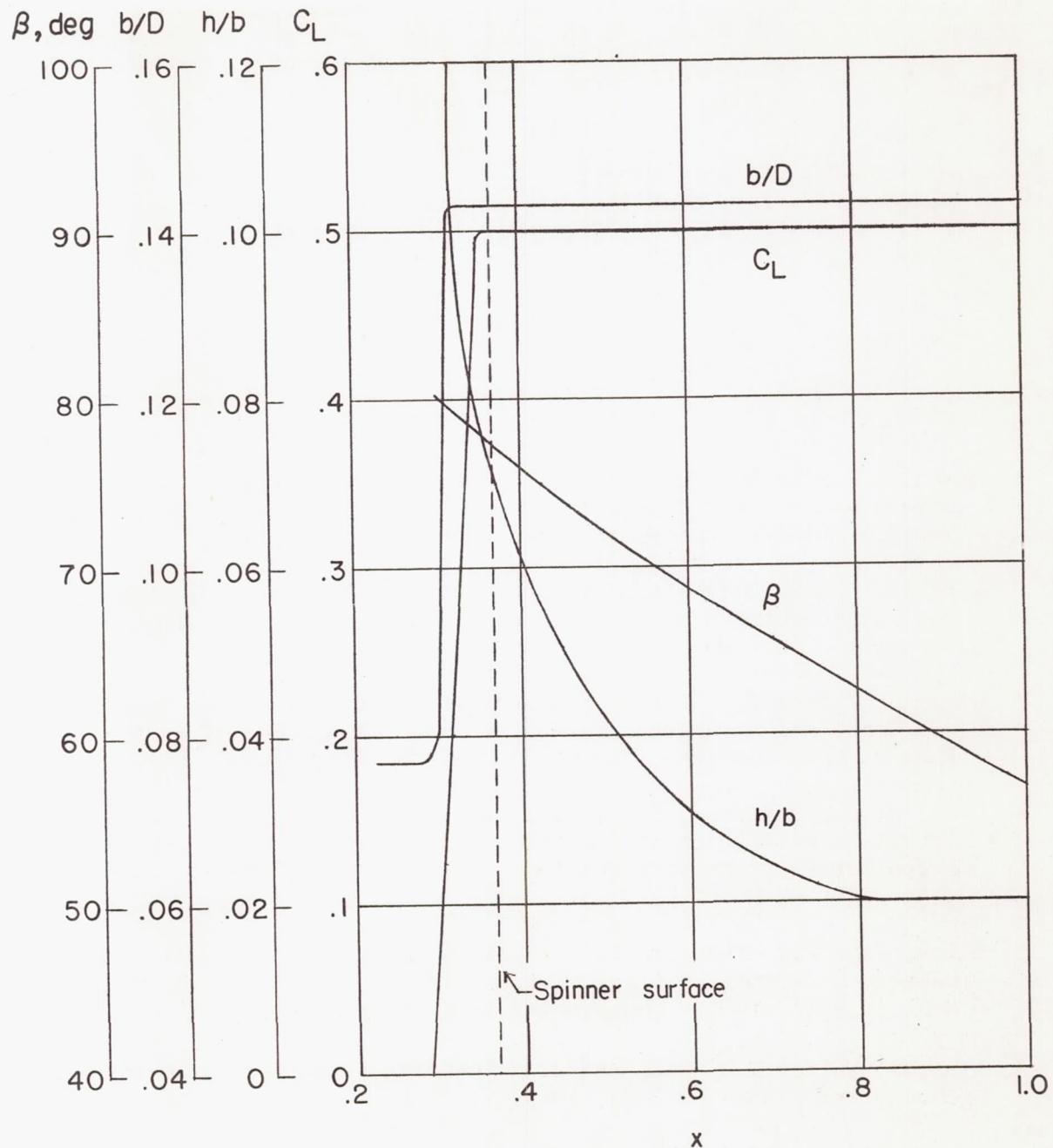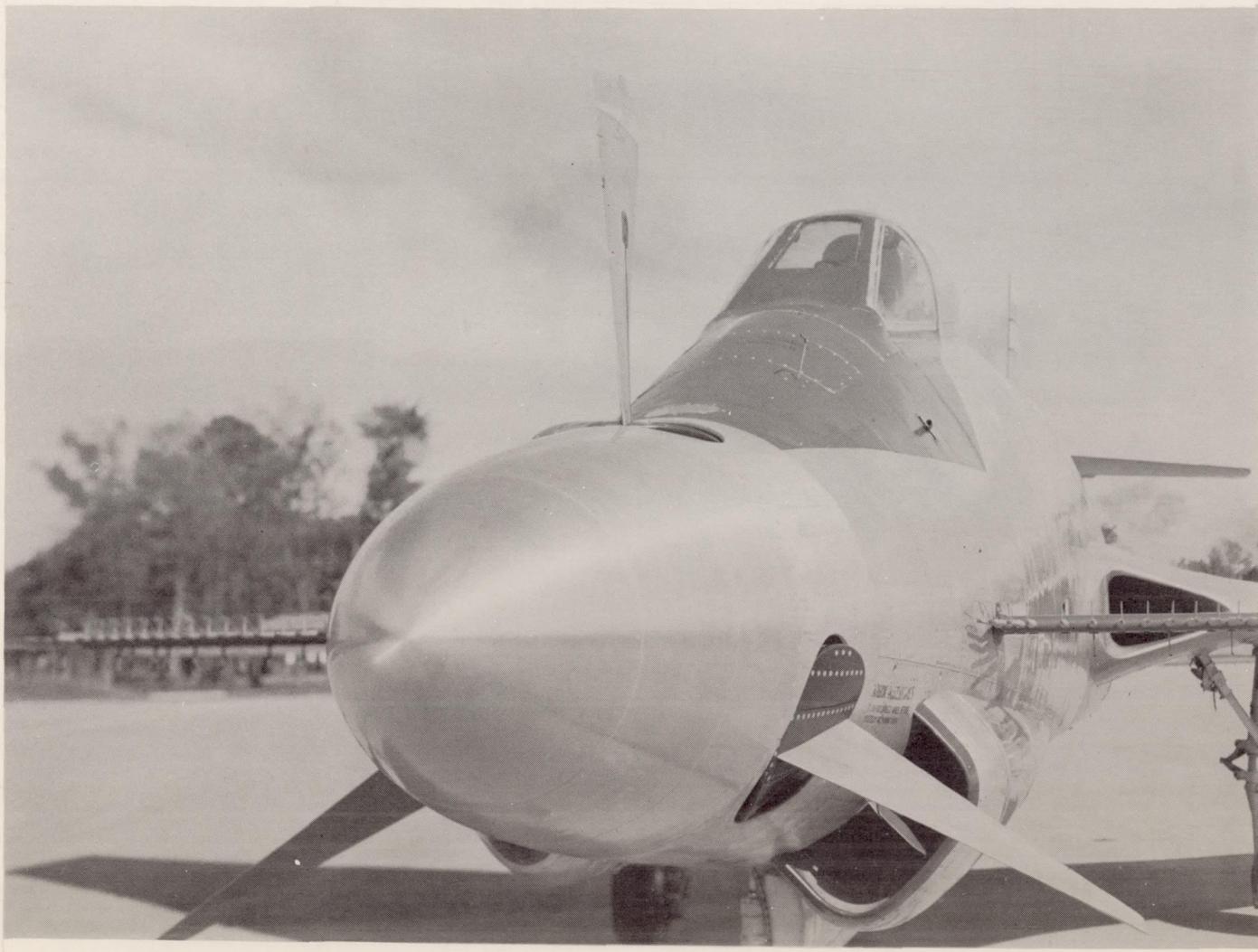
Figure 1.- Blade-form curves for 6.85-foot-diameter propeller designed for an advance ratio of 4.0.

L-57-4962

Figure 2.- The 6.85-foot-diameter propeller and elliptical spinner installed on the XF-88B propeller-research vehicle.
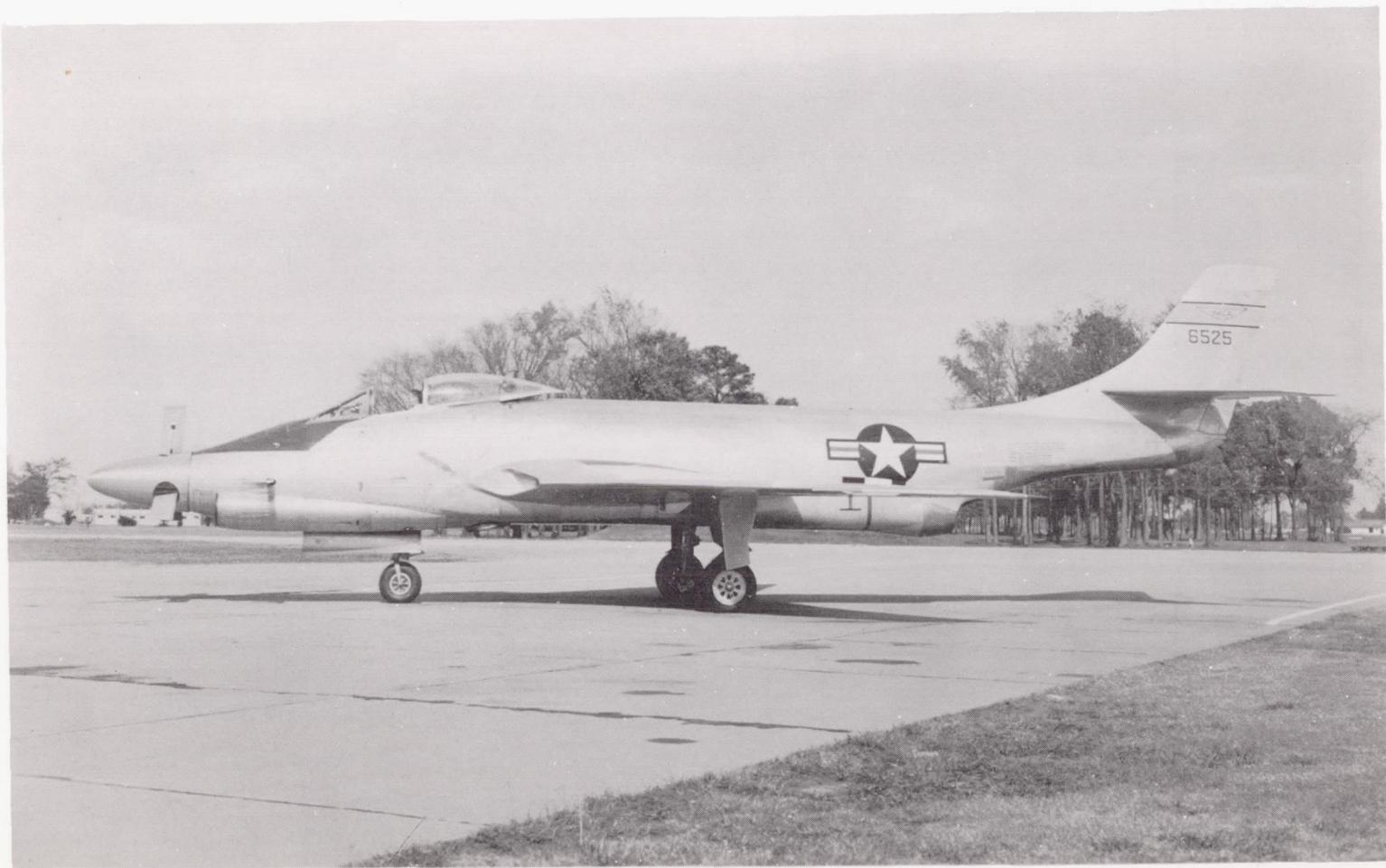
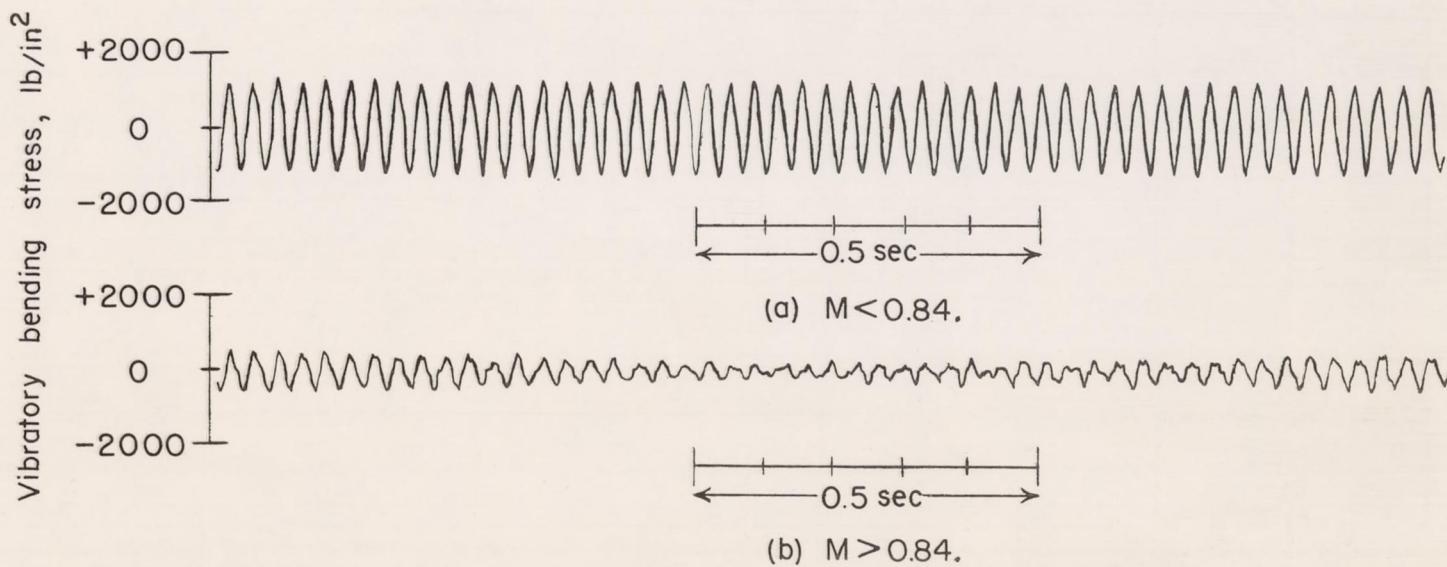Figure 3.- The XF-88B propeller-research vehicle with test propeller. L-57-4959

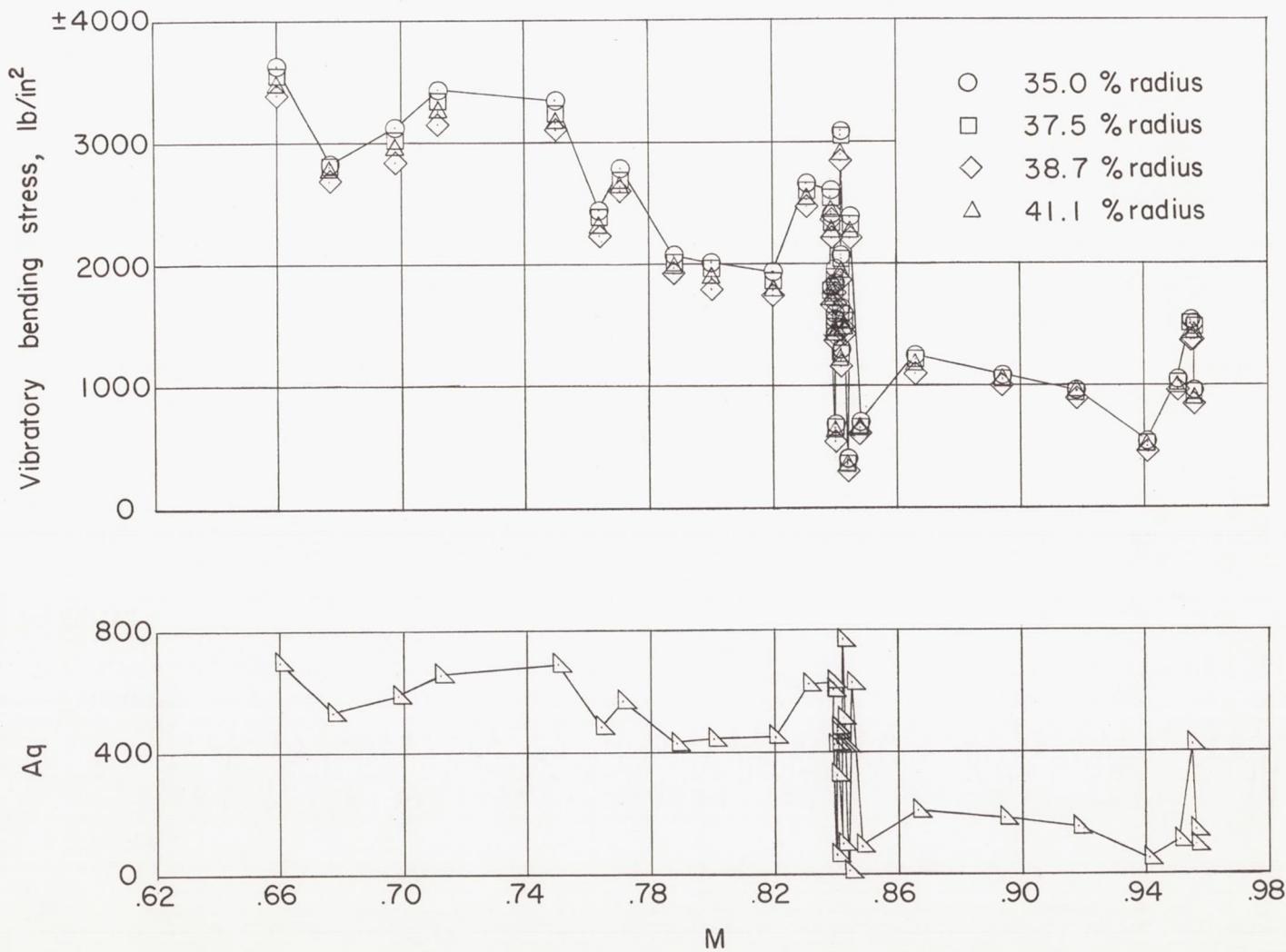Figure 4.- Typical examples of wave shape of vibratory bending stress.

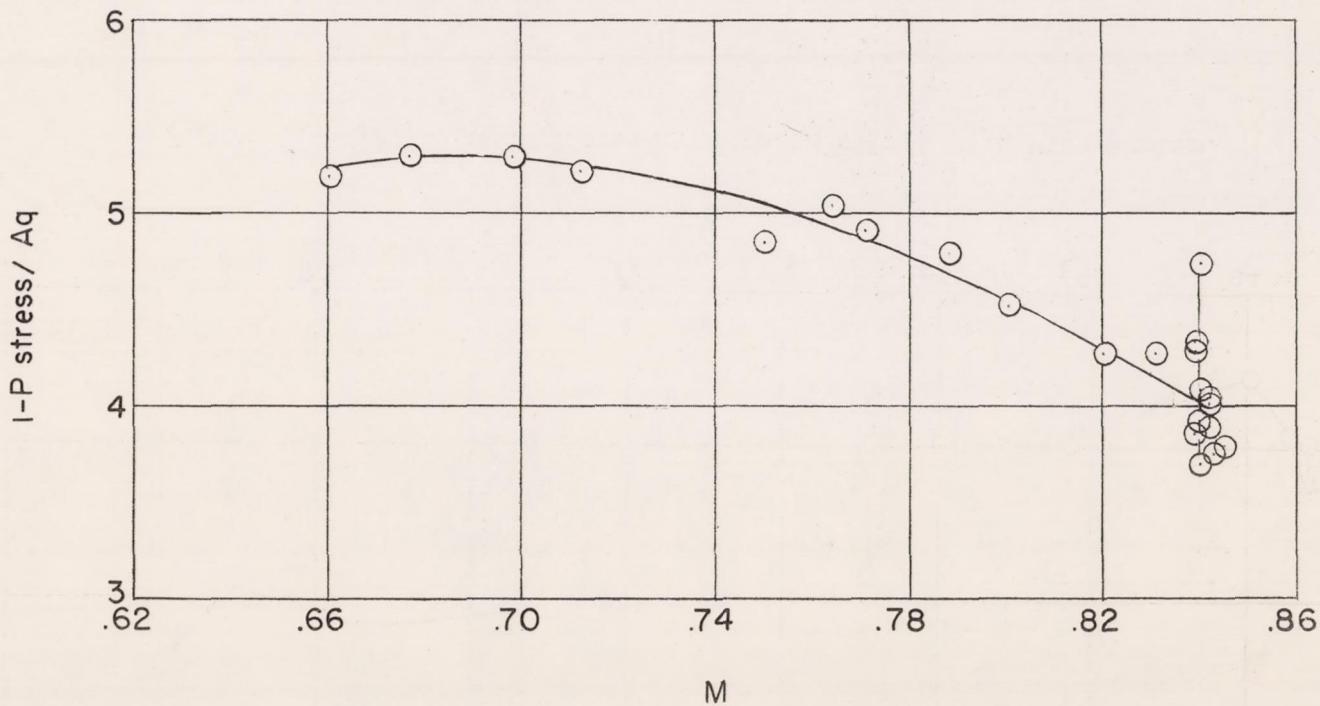Figure 5.- Variation of maximum vibratory bending stress and excitation factor Aq with Mach number.

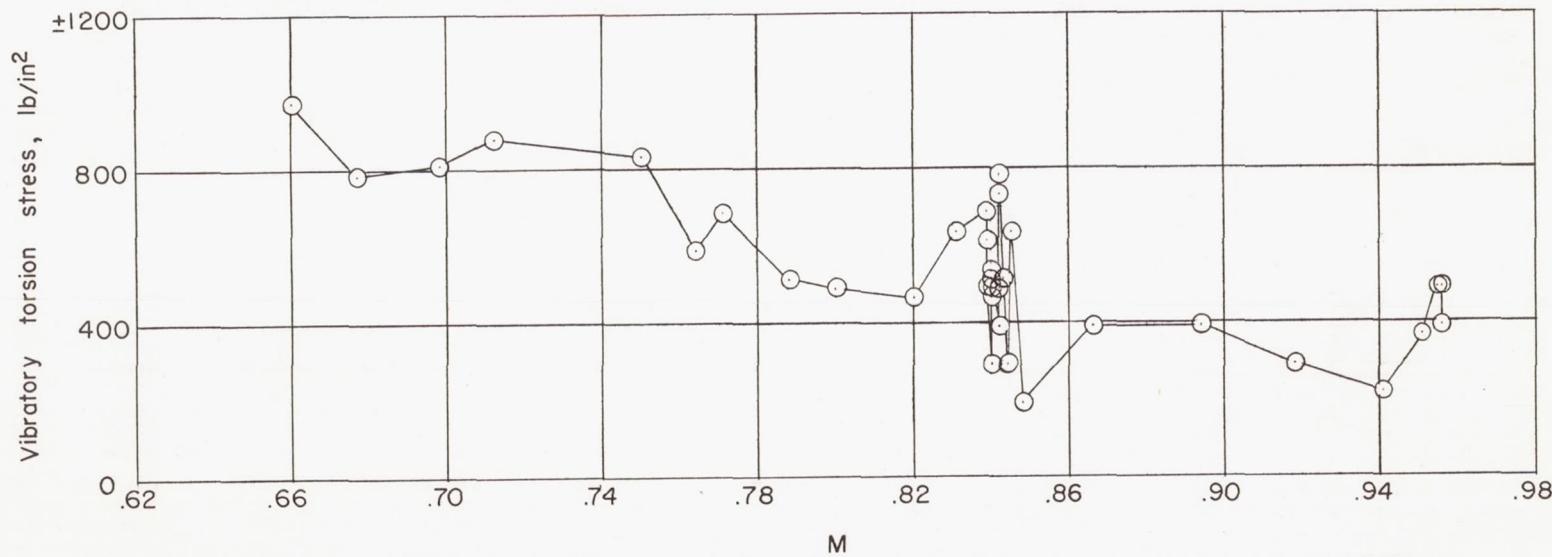Figure 6.- Variation with Mach number of ratio of 1-P stress to Aq measured at 35-percent radius station.

Figure 7.- Variation of vibratory torsion stress with Mach number.